A GENERAL OVERVIEW ON THE BUILDING CONSTRUCTIONS IN CHINA

D.K. Liu and M. Lin
Architecture Engineering College, Harbin Engineering University, Harbin, Heilongjiang, China

W.K. Chow
Areas of Strength: Fire Safety Engineering, Research Centre for Fire Engineering
Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Economics in the Far East is growing rapidly. Many big and new construction projects are found in densely populated areas. With the increase in the number of fire incidents, there are safety concerns.

Structural stability is important in building engineering, bridge works, highway and urban road engineering, railway constructions, tunnel and underground space constructions, hydraulic works, harbour works, ocean engineering, and drainage works in case of fire. To determine proper design for protecting the structures against fire, a review on different structural designs is necessary.

In this paper, different types of building engineering in China are briefly described. Building materials used are reviewed. Examples of new buildings are listed.

1. INTRODUCTION

The number of fires from accident, arson or terrorist attack, appears to be increasing [1] since 1996 after the big Garley Building fire [2] in the Hong Kong Special Administrative Region (formerly Hong Kong). There are so many big city groups in China with complicated building structures such as super tall buildings [3]. Fire safety has become a hot topic that both citizens and government officers are very concerned about. The fire safety provisions might be installed only for satisfying the minimum requirement. A typical scenario was considered, perhaps for reducing the project cost. This is not satisfactory, as the building property owner would control it for a much longer time. As a result, many projects would upgrade their fire safety, even those buildings in operation.

The following functional requirements should be satisfied in designing building engineering. Safety and reliability of the building must be ensured during and after construction if the structural components are not to be damaged in a fire, and the whole structure not to be collapsed. Requirements of the users have to be provided. Deformation or vibration is limited to certain values to make people feel safe, say under wind loading, fire or earthquakes.

Cost is another factor, aiming at providing optimum safety, reliability and suitability in the most economic way. Usually, the lowest construction cost is welcomed in project development. However, safety, reliability and suitability for use might require higher cost if protection is not just on providing minimum installation based on a typical scenario.

A safe and reliable structure means the probability of the structure to reach its limit state is sufficiently low. ‘Limit state’ means that in exceeding certain specified limits, the whole building or part of the structure would fail to perform a certain function of the design. This specified limit is the limit state for that particular function.

There are two kinds of limit states:

- Bearing capacity limit state refers to the situation where the structure or the structural component has reached its maximum load bearing capacity (or maximum strength). Examples are stressing concrete columns or fracturing of beams.
- Service-ability limit state, meaning that the structure or structural component has reached the situation that it cannot function properly. Examples are badly deformed or cracked beams, or cracks appear in a water pool.
In following the specified requirements in the current code on structural design in China, a building structure should satisfy the following functional requirements:

- Able to bear all possible actions under normal construction and usage;
- Good performance under normal usage;
- Good durability under proper maintenance;
- Able to maintain overall stability during and after sudden incidents.

It is not possible to design a structure which is 100% safe. In fact, ‘zero accident rate’ can never be achieved. The objective is to ensure that the failure rate of the structure is within an acceptable level.

Semi-probabilistic limit states design method is adopted in the current structural code in China. Frequencies of occurrence of different limit states are based upon. Together with engineering experience, a design load is determined to ensure that the component strength would satisfy a safety level. For example, in the China code ‘Load code for the design of building structures’ (建筑结构荷载规范), the load value refers to the possible maximum load of the structure under normal usage or within a specified usage time. Under certain circumstances, the structural loading experienced might exceed this maximum load. A “safety factor” is then adopted to increase the design load. In the code, the value of component strength is specified based on a confidence level of 97.73%. In practice, different factors such as uncertainties in construction and homogeneity of materials, a “safety factor” of the component strength has to be considered. Depending on the importance of the structure, “additional safety factors” might be considered.

To provide better fire safety, structural stability is designed not just for protecting against typical scenarios. Better understandings of the building construction materials and structural designs used are necessary. Typical examples should be considered. Summarizing these points becomes the objective of the paper.

2. STRUCTURAL MATERIALS COMMONLY USED

Structural materials commonly used in China [5-7] are summarized in the following.

2.1 Bricks, Tiles, Sand, Stones, Lime and Cement [6]

Bricks, tiles, sand, stones and lime are taken as ‘local materials’. These materials are relatively cheaper and large quantities are required. Therefore, it is better to get these materials locally or from nearby regions.

Materials which can bond granular materials (such as sand or gravels) or materials in small pieces (such as bricks or masonries) together into a composite material are called binding materials. Typical examples are lime and cement.

2.2 Steel Products

Steel products [5] used in building engineering as in Fig. 1a are shaped steel (e.g. steel strip, angle steel, I-steel), plates and tubes used in steel structures; and different reinforcing bars and wires in reinforced concrete. These are low-carbon steel with less than 0.22% carbon content. There might be small amount of manganese, silicon, and vanadium. The ultimate tensile stress (UTS) of low-carbon steel is about 235 N/mm² or MPa; but can go up to 335 to 400 N/mm² for low-alloy steel. The materials are made into different forms and shapes to give the required structure. Steel wires can be cast into concrete to make reinforced concrete. Concrete can also be pumped into steel tubes to make concrete-filled steel tubes (CFST).

Steel products are manufactured under tight quality control to ensure uniformity and quality. Reliable tensile, compressive, bending and shearing strengths would be achieved. They can bear relatively strong forces and vibrations under normal temperature. With good plasticity and good toughness, steel products can be easily processed, cast, forged, welded, riveted and cut; and are convenient to assemble. In addition, the properties of steel can be modified or controlled within a large range through heat treatment. However, unprotected steel has poor fire resistance, high maintenance cost, and gets corroded readily.

2.3 Concrete and Mortar

Concrete [5] is commonly used as a building material as in Fig. 1b. It is a composite material made by suitable mixing ratios of binding material, aggregates and water, through batching, mixing, formworking, placing, compacting, shaping and curing. The concrete used in building structure is cement concrete with cement being the binding material, aggregates (including fine sand and gravels) and water. There are also lightweight concrete made from light aggregates for thermal insulation, and asphalt concrete made from bitumen and aggregates for paving roads.
The strength of the cement concrete used in building structures is generally C20-C40, or even up to C60-C80 (compressive stress of 150 mm concrete testing cubes are 20 N/mm², 40 N/mm², 60 N/mm² and 80 N/mm² respectively). The compressive strength of C20-C40 concrete at the center is about 13.5 to 27 N/mm², and the tensile strength is 1.5 to 2.5 N/mm². Since the tensile strength of concrete is weak, reinforced concrete structures by combining concrete with steel formworks are used.

Concrete takes the advantages of being flexible, easily be moulded into different shapes of the formworks. It is durable, not combustible, easily be obtained locally, and cheaper but stronger than bricks and timber. Concrete structure has good overall performance, so is widely used in building construction. However, the manufacturing procedures are rather complicated and take a longer time. Cracks might be found while making them in sites.

Mortar [6] is made by mixing binding material such as cement, lime and gypsum, fine aggregates and water in appropriate ratios. Mortar differs from concrete in not having coarse aggregates; it is regarded as a special type of concrete, called fine-aggregate concrete.

Based on the different binding material used, mortar can be classified into cement mortar, lime mortar and mixed mortar. Mixed mortar can be further divided into cement-lime mortar, cement-clay mortar, and lime-clay mortar.

Mortar is graded according to its compressive strength, or called the mortar strength, represented by ‘M’ and its compressive strength (MPa). The strength gradings are M2.5, M5.0, M7.5, M10, M15 and M20, meaning 2.5 MPa, 5.0 MPa, 7.5 MPa, 10 MPa, 15 MPa and 20 MPa. Mortar of lower grades, such as M0.4 are taken out from the current code [8] ‘Code for design of masonry structures’ (砌体结构设计规范).

2.4 Masonry

Masonry [5] used in building structures as in Fig. 1c are composite materials made by piling up and binding pieces of materials made of timber, bricks, clay, concrete and industrial wastes with binding materials such as cement, lime and mortar. There are many different types such as solid or hollow brick masonry, small and medium concrete masonry, and silicate masonry. However, they are weak in strength. For example, the compressive strength and tensile strength of brick masonry are only 1.5 to 4.5 N/mm² and 0.15 to 0.3 N/mm² respectively.

The advantages of masonry are that the materials can be obtained locally in places with granite structure. They might be cheap, simple and convenient to construct, sound and thermal-insulating, fire resistant, and durable. However, due to its weak strength, clumsy structure, possible competition with agricultural land, its use has been restricted. Besides, due to the large workload in construction, there are problems on quality during the construction.

2.5 Timber

Timber [5,6] used in building structures as in Fig. 1d mainly comes from the tree trunks. Trees are classified into two main types: coniferous (temperate) trees and deciduous (tropical) trees. Coniferous trees have a straight, tall and large trunk; smooth grain; and uniform quality to give softwood. Softwood might not be soft and there is only one type of longitudinal cell structures called tracheids. Typical examples are pine, fir and cypress. Tropical trees would give hardwood, with two types of longitudinal cells, fibres and vessels. They have shorter and harder trunk which are more difficult to process. The wood might not be hard. Typical examples are elm, fraxinus mandshurica and xylosma japonicum. Different sizes of timber are: log (120 mm or larger in diameter), square timber (square cross-section of length 100 mm to 200 mm), bar timber (width not larger than two times the thickness), and timber plates (thin boards of thickness less than 35 mm and width larger than two times the thickness).

Timber is an anisotropic material with both along and across the grain. Cutting them along the directions of along the grain or across the grain would have different properties. Conversion would affect the properties of the final product. Along the grain of fir has a tensile strength of 65 to 75 N/mm² and a compressive strength of 80 to 120 N/mm². But along the grain has poorer strength. Timber in along the grain is not allowed to be under tension if used for load bearing. Factors affecting the strength of timber include the moisture content (weaker strength with higher moisture content), temperature (weaker strength with higher temperature), loading time (weaker strength with longer continuous loading time), and timber defects (e.g. knots, rot, cracks, warp and plant diseases).

The advantages of timber include relatively high ratio of strength to unit weight, light own weight of the structure, easy to process, and short construction period. On the other hand, its disadvantages are combustible, easily ignited, rot and deformed.
Fig. 1: Different types of structural materials and composite structures [5]
The general situation on building material selection in China is:

- Steel products are superior. Steel structures were not so popular in the past due to limited production and high cost in China. With the increasing production in modern China, steel structures have prospective development in the construction industry.
- Timber structure has limited applications now due to limited natural resources.
- Concrete has a strong compressive strength but a weak tensile strength. Reinforced concrete combining the advantages of steel and concrete is widely applied. It can also reduce the steel content for lowering the construction cost.
- Although masonry is weak in strength, it is still popularly used in small and medium construction projects because it is inexpensive, simple and convenient to construct. Further, many towns are sited on granite sites, giving abundant local supplies.

A comparison of the strength of the four commonly used materials [5] is shown in Fig. 2.

In recent years, composite structures are developing rapidly. Examples include composite columns made of concrete and shaped steel; and concrete-filled steel tubes as shown in Figs. 1 e to g.

![Comparison of four commonly used materials](image)

**Fig. 2: Comparison of four commonly used materials [5]**
3. MAJOR STRUCTURAL COMPONENTS

In general, the structure of a building [5,6] is composed of the following components as shown in Fig. 3:

3.1 Slab
Slabs [5,6] are components with a relatively large plan size and small thickness for bearing the bending forces. Slab is usually installed horizontally, but sometimes in a slanted position (e.g. staircase slab); or even vertically (e.g. wall slab). It is usually applied in floor slabs, roofing slabs, base slabs and wall slabs. It bears the load on the floor slab and those vertical to the slab surface (including permanent load of the floor slabs, floor level and ceiling; and variable load such as people, furniture and equipment). The length and width of a slab are much larger than its thickness. The slab would be bended or deformed when loaded.

There are one-way and two-way slabs. Load on a one way slab is transferred along one direction to the supporting component. Example is a rectangular slab supported on two sides. Load on a two-way slab is transferred along two directions to the supporting component. Example is a rectangular slab supported on four sides. When the length of the slab is much longer than its width, the load on the slab is mainly transferred along the width to the supporting component. The load transferred along the length is very small and can be neglected. Such slabs supported on four sides are also regarded as one way slabs. Theoretical analysis shows that for a slab of \( l_1 \) length and width of \( l_2 \), load transfer along the width \( l_2 \) does not exceed 6% when \( l_2 / l_1 \) is larger than 2. Such slabs supported on four sides are regarded as one way slabs. The slabs are two-way slabs when \( l_2 / l_1 \) is smaller than 2.

3.2 Beam
Beams [5,6] would bear the pressure from the slabs and dead weight. Beams are usually installed horizontally, but sometimes in slanted positions such as staircase beams. The cross-sectional height to span ratio of a beam is generally 1/8 to 1/16. Beams with a height to span ratio larger than 1/4 are called deep beams. The cross-sectional height of a beam is usually larger than the width of the cross-section. But for some constructions with the width larger than the height, those are called flat beams. When the height of a beam changes along the axis, they are called beams of variable sections. The loading direction of a beam is perpendicular to the beam axis, mainly for withstanding the bending and shearing forces.

3.3 Wall
Walls [5] would bear the pressure from the beams, slabs and dead weight. Both the length and width of a wall are larger than its thickness. The loading direction is parallel to the wall surface. Its function is to stand the pressure (when the load exerts on the axis of the wall), and sometimes the bending force (when the load deviates from the axis).

3.4 Column
Columns [5,6] would bear the pressure from the beams, slabs and dead weight, and sometimes the vertical component of a bending moment. The cross-sectional dimension of a column is much smaller than its height, and the loading direction is parallel to the column axis. When the loading direction is along the axis, the column axis is under axial pressure. When the loading is parallel to and not coincides with the axis, the column is under eccentric pressure (pressure and bending forces).

3.5 Foundation
Foundation [1] bears the pressure from the walls and columns. Non-uniform settlement might be resulted due to the complicated soil composition of the foundation and structure. During earthquakes, liquefaction might occur for soft foundations. The components described above are planar rectilinear components. Other than those, rectilinear polar curved surface and curvilinear components are also commonly used in different kinds of buildings as shown [5] in Fig. 4.

3.6 Pole
The cross-sectional dimension of a pole [5,6] is much smaller than its length. Poles would bear mainly the axial compression or tension. Poles are often used to construct a plan truss space lattice grid in building structures to bear the vertical load. In analyzing a truss space lattice grid, the loads are concentrated at the nodes where the poles are joined together. The poles between two nodes would not bear the load.

3.7 Arch
Arch [5,6] is composed of curvilinear components and its support, mainly bears the axial pressure. The main difference between an arch and a beam is that an arch would produce a horizontal anti-force under a vertical load. Under such horizontal anti-force, the bending moment of an arch is much smaller than that of a beam with the same span and load. The cross-section of the arch structure is ensured to bear mainly the axial forces. In
comparing with a beam of the same span, less materials are required. This is very obvious when the span is large.

Fig. 3: Structural components of a typical multi-story building [5]
Therefore, arch is widely applied in bridges but not in buildings. Typical building applications are circular lintel for doors and windows in brick-concrete structures, and large-span arch structures. Based on the number of hinges, arches can be classified as three hinged arches, hingeless arches, arches hinged at ends, and two hinged arches with tie rod. Among which, three hinged arch is statically determinate, the others are statically indeterminate.

### 3.8 Shell

A shell [5,6] is a space structural component composed of curvilinear plates, supporting beams and arch truss. It mainly bears pressure under loading, similar to an egg shell where the space structure can bear very high load but constructed with a relatively thin structural thickness. Similar to an arch structure, supporting elements of a shell can stand sufficiently high load to give rigidity of the shell structure.

In building constructions, trusses and space lattice grid composed of slabs, beams and poles are the horizontal structures for the roofs. Different types of roofs [5] are shown in Fig. 5. Well-tube structures composed of columns, walls and external walls are the vertical structures of a building. These are the main structural elements which have to bear the whole weight of the building and then transfer it to the foundation. Under the action of wind or earthquake, they are responsible for withstanding the horizontal load. The foundation can be a horizontal structure such as a raft foundation, a combined foundation or a strip foundation. It can also be a vertical structure such as a single foundation under the column, pile foundation in soil, or a box foundation that has both characteristics of horizontal and vertical structures are shown [5] in Fig. 6.
Fig. 5: Different types of roof [5]

(a) Strip foundation  (b) Raft foundation  (c) Box foundation

Fig. 6: Building foundation [5]
4. TYPES OF BUILDING CONSTRUCTIONS

Building constructions can be classified [5-7,9] according to the use, number of stories, structural forms and loading elements, and the materials used.

4.1 Classification Based on the Building Usage

- Residential buildings such as villas, hostels and apartments. Although the interior dimensions are small, the layout is very important. There are requirements on the direction orientation, daylighting, thermal insulation, sound insulation, and fire protection. The main structural components are floor slabs and walls. Such buildings in China might be lowrise of 1 or 2 levels, or highrise from 10 to 20 levels.

- Public facilities such as exhibition halls, theatres, sports stadiums and terminals. These are places where occupant loading is expected to be high. The indoor space, size, and crowd flow might be very large. Therefore, fire safety is of critical importance and very tight requirements are set up on its functions and facilities. The main body structures are large-span frame joining the beams and columns together, lattice grid, arch or shell structures. Usually, public facilities have only several stories, but can be very tall.

- Commercial buildings such as shops, banks, offices, guesthouses, and multi-purpose complexes integrating offices, apartments, places for entertainment, and carparks. These are places where large number of people would be staying inside. Requirements are similar to those for public facilities. There are now many tall buildings in China requiring high quality on structural system and forms.

- Educational or sanitary buildings such as libraries, schools, laboratories and hospitals. These have to be designed specifically to cater for the specific functional purposes. For example, there are stack rooms in a library; special facilities in a laboratory; clients and various kinds of medical equipment in a hospital; students in a school. Therefore, a high level of safety, including fire safety, is demanded. Frame structure is frequently adopted as the main structure. The building usually has 4 to 10 levels.

- Industrial buildings such as heavy machinery plants, factories, textile mills (single-story light industry), pharmaceutical factories and food products factories. These buildings have to bear huge static and dynamic loads, and vibrations. A huge space is needed for production. Also, there are specific requirements on temperature and humidity. They are required to be dustproof and fireproof, and possess the capability to resist explosion. Single-story industrial buildings usually adopt the hinged frame (also called truss) structure, while multi-story industrial buildings usually adopt the rigid frame structure.

- Agricultural constructions such as grasshouses and stock farms. Light steel structures are usually employed. Thermal environment, ventilation and fire safety should be provided properly for such constructions. Special research activities are required.

4.2 Classification Based on the Number of Stories

Buildings can be classified [6,9] into single-story buildings, multi-level buildings and high-rise buildings. The definitions for multi-level and high-rise buildings are different in different countries. In China, buildings with less than 10 levels are regarded as multi-level buildings. Multi-level and high-rise structures are usually found in residential buildings, shopping malls, offices and hotels. Common forms of multi-level structures are mixed structure and frame structure.

According to the codes in China, residential buildings with 10 or more stories; and public and integrated buildings with height exceeding 28 m are regarded as high-rise buildings. High-rise buildings can be further divided into two types: those lower than 200 m with less than 50 stories are referred to as high-rise buildings; while those exceeding these values are referred to as super high-rise buildings.

Single-story buildings can be divided into general buildings and large-span buildings:

General single-story buildings can be subdivided into buildings for civil use and industrial factories. Brick masonry structure is commonly used in single-story buildings for civil use. Both brick walls and reinforced concrete roof slabs are used. Examples are single-story residential buildings, public constructions and villas. Reinforced concrete or steel structural columns are commonly used in single-story industrial factories. Steel roof
truss structures can be divided into bent frame structure and rigid frame structure. Bent frame structure means the columns and foundation are rigid connection, the roof truss and the top of the columns are hinged connection. Rigid frame structure is also called frame structure, meaning that the beam or roof truss and the columns are rigid connection.

Large-span structures are commonly found in exhibition halls, sports stadiums and hangars. There are many types of such structures including lattice grid structure, cable structure, thin-shell structure, concrete arch truss, pneumatic structure, membrane stress structure.

- Lattice grid structure
  Lattice grid structure [6] is the most common form of large-span structure. It is also called a space truss because of its space structure. Steel tubes or shaped steel are usually used for the poles, and assembled in sites. It is composed of a plane truss, square pyramid and triangular pyramid. The nodes are either welded steel plate joints or welded hollow spherical joint.

- Cable structure
  Cable structure [6] means to “transplant” the suspended cable of a bridge into a building. This is a good example of using a structural form in different types of constructions.

- Thin-shell structure
  Thin-shell structure [6] usually takes the form of a dome, cylindrical shell, folded-plate, double curvature shallow-shell, hyperbolic paraboloid shell. Domical vault structure is an axially symmetric structure, under axially symmetric load the force can be resolved along the radial and circumferential directions. Radial forces are forces acting along the radial direction, balancing the downward vertical load, which must be pressure. Circumferential forces are forces along the longitudinal direction. When the circular roof is under a vertical load, the upper part would be contracted due to circumferential pressure. The diameter would be reduced. The diameter of the bottom part near the supporting portion would increase. In other words, circumferential stress would be induced at the upper part while the lower part is under circumferential tensile force. There is a plane in between where co circumferential pressure becomes tensile force. The circumferential stress at that plane is zero, being called the “transition joint”.

- Concrete arch truss
  Concrete arch truss [6] was used frequently in the past, but seldom used now due to its heavy weight and complicated construction. The largest arch truss with the largest span in the World was built at a hangar in Belgrade, Yugoslavia. That is a prestressed concrete truss structure with a span of 135.8 m.

- Pneumatic structure
  Pneumatic structure [6,9] is also called Pneumatic membrane structure. Air is filled in a glass fibre reinforced plastic membrane or a nylon cloth, taking the shape of a covering for the structural space.
  The Tokyo Dome, of diagonal span 200 m and a height of 6.07 m from the indoor ground level to the ceiling, is not supported by columns. There is a membrane roof structure making use of the pressure difference between indoor and outdoor. This gives a huge elliptical roof of area 30,000 m², being the first air-inflated membrane structure reinforced by suspended cables used in multi-purpose all-weather sports stadium in Japan. There are 14 steel cables on each of the two sides (a total of 28). The glass fibre cloths are coated with Teflon.

- Membrane stress structure
  Membrane stress structure [6,9] is a space structure constructed by welding thin steel plates together. A stressed membrane roof of diameter 117 m and height 35.7 m was built in 1959 in Baton Rouge, Louisiana, USA. A short-range truss system of an external tubular skeleton was used to support 804 hexagonal steel plates of length 4.6 m, and thickness larger than 3.2 mm. The steel pipes are of diameter 152 mm and wall thickness 3.2 mm. This is the first large-span building with membrane stress structure.

4.3 Classification Based on the Structural Forms and Load Bearing Systems of the Main Structure

Structural systems [6,7] are classified into wall structure (also called shear wall structure), frame structure, tube structure, combined frame-shear wall structure, frame-tube structure, deep beam (substituting wall) structure, lattice grid structure (for the roof), arch structure, space thin-shell structure, space folded plate structure and steel cable structure [5] as shown in Fig. 7.
4.4 Classification Based on the Materials Used for the Structure

Common structures [5-7,10] are masonry, reinforced concrete, steel, concrete-filled steel tube, and wood.

- Masonry structure: where walls and columns built from pieces of materials and mortar are used as the main load bearing components of the building. Masonry structures include brick masonry, building blocks masonry and stone masonry structures.
- Reinforced concrete structure: made of reinforced concrete or prestressed concrete; mainly used in frame structure, shear wall structure, tube structure, space thin-shell and space folded plate structure.
- Steel structure: made by joining various kinds of shaped steel or steel tubes; apart from the abovementioned wall structure, thin-shell and folded plate structure, others can be made with steel structure.
- Concrete-filled steel tube: where concrete is filled within the steel tubes. Its applications are similar to those of steel structure.
- Timber structure: made by joining together square timber, log, bar timber, and plank. Timber structures were used frequently in ancient China (e.g. palaces, temples, pagodas, dwelling houses), but not so nowadays due to limited supply of natural resources.

Brief introductions to building structures based on this classification will be discussed in the following sections.

5. MASONRY BUILDING STRUCTURES

Masonry structures [5-7] can be categorized into non-reinforced masonry without reinforcement in the masonry structures; and reinforced masonry with reinforcement used as the main load bearing components. These include net-shaped reinforced masonry columns, horizontal reinforced masonry
walls, brick masonry and reinforced concrete surface layer or reinforced mortar surface layer composite masonry columns (walls), brick masonry and reinforced concrete column composite walls, and reinforced building blocks masonry shear wall structure. It can also be further divided into horizontal and vertical reinforced masonry. Horizontal reinforced masonry refers to those net-shaped reinforced masonry columns and horizontal reinforced masonry walls. Vertical reinforced masonry are those structures with reinforcing bars in the shear wall to resist shearing stresses.

Masonry structures can be divided into transversal bearing wall system, longitudinal bearing wall system, transversal and longitudinal bearing wall system, internal frame-external masonry wall system, and the supporting system with a bottom frame and an upper masonry [7,11] as shown in Fig. 8.

- Transversal bearing wall system:
  The transversal wall is responsible for bearing the load. There are fixed room sizes at shorter intervals (say 3 to 4.5 m in general) between the transversal walls. This system is suitable for residential buildings to give large space rigidity and good overall performance. It can stand horizontal actions due to wind and earthquake; and more capable of resisting foundation’s non-uniform settlement.

- Longitudinal bearing wall system:
  Longitudinal walls have larger intervals to give greater flexibility for space allocation. It is usually designed in academic buildings, laboratory buildings, and small to medium-sized industrial factories. There is less space rigidity with poor overall performance. The positions of doors and windows on the vertical wall are constrained to some extent.

- Internal frame-external masonry wall system:
  Boundary columns can be omitted and comparing with the longitudinal bearing wall system, larger space can be provided without increasing the beam span. The room has poorer space rigidity. Non-uniform settlement might occur due to the deviations of the foundation under walls and the column foundation.

- Supporting system with a bottom frame and an upper masonry:
  This kind of system is favored by the developers because a large space can be provided at the bottom part. However, there are problems in protecting against earthquakes. A shear wall has to be installed at the bottom part to give better anti-seismic capability.

Masonry structure is the earliest building construction in history, being an important symbol of human civilization. An example is the Great Pyramid of Khufu of height 146.6 m built in 2000 B.C. in Egypt. Also, the Hagia Sophia Church built in 537 A.D. in Istanbul is a magnificent building complex of semi-circular arch structures constructed by brick masonry. It has a diameter of 30 m, and the distance from the ground to the ceiling is 50 m. This building complex is still erected for public viewing. There were many great masonry structures built in ancient China. Examples are the Wu Liang Hall (无梁殿) in Ling Gu Temple (灵谷寺) in Nanjing built in the Ming Dynasty. Brick arches were the main structure. The outer eaves, dougong*, purlin and square pillars were made of brick stones for supporting the timber structures. The Tower of Kai Yuan Temple (开元寺塔) in Ding County, Hebei (河北定县) built in 1055 was the highest masonry structure at that time. It had a brick masonry double-story tube structure of height 84.2 m.

The 16-level Monadnock Building built in 1891 in Chicago, USA was the highest office building by that time. Lifts installed in there are still in use. In 1932, reinforced masonry proposed by B.N. Hexpacab of the former Soviet Union was promoted. After the 1950s, 19-story and 24-story tower-like housings with a wall thickness of 38 mm were built in Switzerland using perforated bricks with a perforation rate of 28% and a compressive strength of 60 MPa. 24-story apartments were also built in America using two 90 mm thick single brick walls with 70 mm reinforced mortar layers placed in between.

Masonry building structures in China have developed since the 1950s, from brick masonry to large vibration brick wall plates, reinforced brick masonry, and then to reinforced concrete masonry [3] as shown in Fig. 9. Examples are the 9-story diplomatic apartments with reinforced brick masonry in Beijing, and the 8-story Daqiao Hotel (大桥旅馆) of hollow bricks in Nanjing. The 12-story residential housings made of brick masonry in Zhongshan, Chongqing is currently the tallest masonry structure in China.

*斗拱 dougong [dougong is a system of brackets in Chinese building; wooden square blocks inserted between the top of a column and a crossbeam] 中国建筑特有的一种构造，在立柱和横梁交接处，从柱顶上加的一层层探出成弓形的承重结构叫做斗拱，通与横之间的方形木块叫斗，合称斗拱。
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(a) Transversal bearing wall system

(b) Longitudinal bearing wall system

(c) Transversal and longitudinal bearing wall system

(d) Internal frame-external masonry wall system

(e) Supporting system with a bottom frame

Fig. 8: Masonry structures [7,11]
6. REINFORCED CONCRETE STRUCTURE

Reinforced concrete structures [5,6] are made of concrete with reinforcement, bar-mat reinforcement or steel skeleton.

Concrete takes the advantages of having good overall performance, low cost, and able to be moulded into different shapes. Reinforcing it with different kinds of steel bars according to the loading condition and practical requirements of the structure and components can give various types of load bearing components for different structural systems with much wider applications. It can be made into prestressed concrete, high strength concrete (above C60) and lightweight concrete (made of light aggregate). Using concrete gives significant effect in upgrading the living style of people by developing civil works. Reinforced concrete structures are now having the most prospective development.

Reinforced concrete structure has the following characteristics:

- It has good durability and fire resistance, requiring not so frequent maintenance as for steel structures. The tensile stress required by the structure would be distributed to the reinforcement. As the steel bars are embedded in the concrete, the materials would not be corroded easily and have better fire resistance. Provided that the concrete layer is sufficiently thick, the steel bar can perform the load bearing function without heating up to the critical temperature at 500 °C to 600 °C within 1 to 2 hours.

- As concrete can be moulded into different shapes, different components can be cast in-situ according to the functional requirements.

- Since concrete structure can be cast in-situ, it has good overall performance including good fire resistance, anti-seismic and anti-explosion capability. Reinforced concrete can be applied in high-rise building structures.

- The cost will be reduced if sand and stones are available locally.
Reinforced concrete structure can substitute steel structures under certain circumstances without using so much steel products.

The disadvantages of reinforced concrete structure are: heavy own weight, poor anti-fracture capability, time and labour-consuming if set form in-situ.

The tallest concrete building in the World at present is the Petronas Towers in Kuala Lumpur, Malaysia. It is a 95-story building of height 390 m (450 m including the mast). The lower part from the ground to the 84th floor was built by concrete structures (C80 to C40 downwards). The upper part was built by steel columns and beams to support the levels above the 84th floor. The whole structure is long and narrow with a height to width ratio of 8.64.

Another public construction building worth mentioning is the National Industrial and Technological Exhibition Centre in France (国家工业与技术展览中心). It is constructed by concrete thin-shell structures with the largest span in the world. It has a triangular plan of length (span) 219 m and a distance of 46 m between the ceiling and the ground. There is a double-layer arch shell supported on three corner button bearings joined by prestressed poles. The two upper and lower layers have a thickness of 64 mm. The total thickness of the shell is 180 mm. The thickness to span ratio is 1:1200, a value 12 times smaller than the thickness to length ratio of 1:100 of an egg shell. It is a good demonstration (as in Fig. 10) how superior a concrete shell structure [5] is.

The 88 levels Jin Mao Tower of height 421 m in Shanghai is the highest composite structure of reinforced concrete and steel in China. Its main structure against lateral forces (resist earthquake and wind) is a concrete core tube made of an extended truss connected to the external eight giant composite columns.

Although concrete structure is suitable for high-rise buildings, fire safety should be watched carefully. When there is a fire, “chimney effect” might be resulted easily at the tall lift shafts. Further, modern high-rise buildings with glass façade might give a pathway for wind induced air flow to facilitate fire spread. In general, concrete has a longer fire resistance period than that of steel structure. But new structures such as the thin-shell structure of the National Industrial and Technological Exhibition Centre in France might give new fire problems not yet encountered. For a shell structure with a thin thickness of only 180 mm (with thickness-to-span ratio even smaller than that of an egg shell), the overall reliability would be reduced in a fire. Questions would be raised on whether the structure is still stable when there is a fire. Fire safety is a concern and people would ask:

How long can a 180 mm thick concrete shell with its base and prestressed poles of length 219 m stand a fire?

Fire safety provisions required for this new type of building structure should be further studied.

7. STEEL STRUCTURED BUILDINGS

These are usually composed [5,6,12] of steel beams, steel columns and steel trusses made from shaped steel, steel tubes and steel plates. The structural components are joined by welding, bolting or riveting. Steel structures are usually used in buildings and other civil engineering constructions with a large-span, tall height, heavy loading and large dynamic forces. Steel structures are applied in:

- High-rise steel-structured buildings
  At present, the top 20 tallest buildings in the world were built by the steel structure or steel-concrete structure. Their heights range from 300 m to 450 m, with 70 to 110 levels. In the early and mid 20th century, super tall buildings were erected in America. With the rapid growth in global economics, more and more super tall buildings are built over the world. Among the top 100 highest buildings in the world, 45 buildings are constructed by pure steel structures, 20 by different forms of steel-concrete structures, and 18 by reinforced concrete.

- Large-span steel structure
  Lightweight high-strength steel structures can reduce the dead weight of the horizontal beams of a large-span structure to obtain large span space to achieve cost-effectiveness.

- Slab-shell steel structure
  Slab-shell steel structures are often used for sealed containers such as large oil tanks and gas containers. It has to bear very high internal forces. Large-diameter blend pressure oil and gas bland pressure pipes are plate-shell steel structures, commonly known as “lifeline” engineering.

- Other steel structures can be applied in roof steel structures, frame steel structures and factories. They are more widely applied in
other aspects such as hydraulic structures, road and bridge works. The structure is characterized by beam and column steel components complemented by floor slabs.

The main beam and column usually adopt the composite beam made from welded shaped steel. The floor slabs are light steel structure.

Fig. 10: Thin-shell structure of the National Industrial and Technological Exhibition Centre in France [5]
In general, steel structures would lose its load bearing function at temperature higher than 600ºC. It is essential to protect the steel structures against heating up in a fire. Steel structures can be protected by applying fire-resistant coating, wrapping the structure or by using more complicated methods such as recycling. Upon completion of the steel structure, maintenance is required to ensure fire protection is not damaged.

At present, the tallest building with only steel structure in the World is the Sears Tower in Chicago, USA. It is a 110-story building of height 442 m as shown [5] in Fig. 11. Typical floors are of 69 m by 69 m square plan, built on a “bundled tube” system of nine squares of 23 m by 3 m. With the increase in height, the individual tubes end at different heights.

The Hong Kong Bank Building in Hong Kong, China is another famous pure steel structure. It is renowned for its dramatic exoskeleton trusses. It is 175 m high with 45 levels above ground and four levels underground [5] as shown in Fig. 12. In order to make the base level a large open space that connects with both the front and rear plaza, a steel structured suspension system is used to restrict the upper frame from reaching the ground. It is a three-dimensional structure constructed by a giant steel column composing of eight columns and five giant steel trusses for bearing the vertical and horizontal loads. The roof for the 84th to 87th floor between the trusses is hung onto the upper truss by means of giant poles.

Fig. 11: The Sears Tower [5]
Fig. 12: The suspension structural system of the Hong Kong Bank Building [5].

(a) Structural plan (13-28)
(b) Longitudinal section
(c) Cross-section
The Federal Reserve Bank Building in Minneapolis, USA, is an 11-story building with a steel suspended cable structure as the main structure [5] as shown in Fig. 13. The span of the suspended cable is 83.2 m. The two sides are supported on the tubular structure with a very large cross-section and rigidity. The horizontal counter-acting stress (pressure) of the suspended cable is bore by the giant steel truss at the corresponding elevation (top). This building might be extended in the future with an arch structure. The counter-acting stress produced by the arch structure at the support pulling horizontally can make the steel truss under tension. In such a way, part of the horizontal counter-acting stress of the suspended cable and arch can be cancelled out.

Space truss structure has been developing fast among the steel structures. It is a space structure built by several trusses joined together through nodes according to certain grid forms. It has the advantages of making use of space to bear forces, light in weight, high rigidity, good overall performance, good anti-seismic and wind bearing capability. It can be used in constructing large-span roofs. Net frames can be divided into plan net frames and net shells. Different steel net frames [5] are shown in Fig. 14.

The Changchun Gymnasium (长春万人体育馆) [5] as shown in Fig. 15 built in 1997 is the highest steel net shell construction in China Mainland. The net shell roof ridge has an arch span of 191.7 m, diameter of 146 m, distance from the ground of 40.67 m, arch thickness of 2.8 m, and a thickness to span ratio of 1:52.
Fig. 15: Cross-section of the Changchun Gymnasium [5]
8. CONCRETE-FILLED STEEL TUBE (CFST) STRUCTURES

Concrete-filled steel tube (CFST) [10] is a structural component made by filling concrete into the steel tube. Usually, steel bars will not be used within the steel tube. There are several types of CFST including square CFST, circular CFST and polygonal CFST.

In a CFST, the steel tube and concrete would restrain each other when under load. Steel tube would restrict concrete, making concrete under complicated stressed condition. In such a way, the strength of concrete is enhanced. The brittleness, plasticity and toughness are improved. The stability of the steel tube is also enhanced to provide CFST with better properties.

In comparing with concrete structure, CFST structures are:

- Safe, economic and reliable high strength concrete (above C50) can be used. The major shortfall of high strength concrete is its high brittleness. To improve its brittleness, over 20% of reinforcing bars by content have to be used. CFST can prevent fracturing due to explosion, it has enhanced compressive intensity and improved ductility.

- Compressive load bearing capability is enhanced which can reduce the cross-section of the column.

- Anti-seismic capability and ductility are enhanced. CFST can be used for columns at higher levels; there is no restriction on the axis to pressure ratio, but only the aspect ratio.

In comparing with steel structure, CFST structures are:

- The steel tubes of CFST are larger in diameter, they are easier to handle during construction.

- Good fire resistance. Concrete inside the CFST can absorb a large amount of heat, so that in a fire, the uneven temperature distribution on the steel tubular column cross-section would increase the fire resistance period. Past experience showed that in order to satisfy the requirement of grade one fire resistance period of 3 hours, 1/3 to 1/2 or even more fire-resistant coating can be saved in using CFST than for steel columns. The larger the diameter of the steel pipe, the more coating can be saved.

- Good stability. Both partial and overall stability of CFST are better than steel structures.

Concrete-filled steel tubes are becoming more and more widely applied in columns of single-story and multi-story industrial factories, equipment structural columns, different types of bracket, pile, space structure, highrise and super tall buildings.

CFST have been used for over 100 years in many countries. Examples are the 46-story Melbourne Public Hygiene Centre (1900); the 58-story Union Square (1989) and the 62-story Gateway Tower in Seattle (1989). CFST have also been developing rapidly in the past 20 years in China. The 72-story Saige Plaza of height 291.6 m in Shenzhen; the 65-story CITIC Plaza of height 236.4 m (2002) and the 57-story Jingguang Plaza of height 220 m (2002) in Guangzhou are the examples.

9. SPECIAL STRUCTURES

Special structures refer to those constructions with special purposes other than houses, underground structures, bridges, tunnels, and hydraulic structures. Common types of special structures are:

- Television (TV) tower

  TV tower [5] is generally of a tubular thick-wall structure or a space truss structure. Usually, there are five main parts including the foundation, base, body, tower and the mast. Toronto TV Tower, the tallest television tower in the World, is a prestressed concrete structure of height 553 m. The cross-section gets bigger and bigger downwards and appears in a Y-shape. There is a large circular tower at the elevation 335 to 365 m, and a small circular tower at elevation 446.2 m, being the highest observation tower in the World.

  The top 10 highest television towers in the world are: Toronto Tower (553 m), Moscow Tower (533 m), Shanghai Oriental Pearl Tower (468 m), Kuala Lumpur Tower (421 m), Tianjin Tower (415 m), Beijing Tower (415 m), Sandi Arabia Tower (378 m), Berlin Tower (362 m), Tokyo Tower (333 m), and Frankfurt Tower (331 m).

- Water tower and cistern

  Water tower [5,6,13] is a tall hydraulic construction for maintaining and adjusting the water quantity and pressure in the piping network. A water tower comprises the tank,
the tower and the base. There are reinforced concrete water towers, steel water towers, and water towers composed of a masonry tower and a reinforced concrete water tank. Same as water towers, cisterns are also used for storing water. The difference between the two is that water towers are supported on frames or tubes, cisterns are usually built on ground level and underground. The largest water tower in the world today is the Melbourne Water Tower with a capacity of 10,000 m³. There is a restaurant at the base.

- Chimney

Being an industrial construction, chimneys [5,6] can be classified into brick chimneys, reinforced concrete chimneys and steel chimneys. Based on the different internal linings, reinforced concrete chimney can be classified into single-tube, double-tube and multi-tube chimneys. Steel chimneys can be subdivided into staywire, self-support and tower frame. The highest chimney in China is of height 270 m located at the Shentou oil factory in Shanxi.

- Silo

Silos [5,12] are used for storing granular and powder substances such as grains, flour, cement, crushed coal and concentrate powder. It can be used as a supplementary facility for corporate adjustment and short-term storage of products; or even for long-term storage of food. In the reinforced concrete granary complex in Lianyungang (连云港) in China, a single silo has an internal dimension of 10 m, wall thickness of 250 mm, and a height of 31.7 m from the funnel opening.

Based on the ratio of the storage height to diameter or width of the warehouse, silos are divided into shallow and deep warehouses. Defining H as the calculated storage height; D₀ as the internal diameter of the circular tubular warehouse; and b₀ as the shorter length (internal dimension) for a rectangular tubular warehouse or the length (internal dimension) of a square tubular warehouse; it is classified as a deep warehouse for $H/D₀$ or $H/b₀ ≥ 1.5$. When $H/D₀$ or $H/b₀ < 1.5$, it is a shallow warehouse.

Shallow and deep warehouses have their own characteristics. Shallow warehouses are mainly for short-term storage. Since the natural collapsing curve of loose substances stored in a shallow warehouse does not intersect with the opposite wall, it can be unloaded automatically. Deep warehouses are mainly for long-term storage. As the natural collapsing curve of loose substances stored in a deep warehouse intersects with the opposite wall, there might be blockage when unloading. Therefore, equipment or labour are required when unloading a deep warehouse [13] as in Fig. 16.

![Fig. 16: Deep and shallow warehouses](image)

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